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UNIVERSITY OF MINNESOTA

# ST. ANTHONY FALLS HYDRAULIC LABORATORY

Project Report No. 131

# A STUDY OF THE FRAGMENTATION OF ROCK BY IMPINGEMENT WITH WATER AND SOLID IMPACTORS

by

John F. Ripken
and
Joseph M. Wetzel



Sponsored by

Advanced Research Projects Agency
ARPA Order No. 1579, Amendment 2
Program Code 1F10



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ABSTRACT


Based on findings in other research areas it was reasoned that water slugs of substantial size (up to 1/2 lb) traveling at moderate velocities (< 800 fps) could impinge on rock with fragmenting pressure. To substantiate this reasoning, a compressed air launching gun was designed and built and an extensive series of impact tests was made on a steel-mounted pressure transducer and on sandstone and limestone targets.

In a very few tests pressure values measured on the steel target exceeded the nominal compressive load limits of the rocks, but on actual rock targets significant fragmentation failed to occur. The basic difficulty was related to an inability to maintain a suitable air-water interface on a traveling water slug containing high kinetic energy. This, together with higher-than-anticipated dynamic failure values in the rock, prevented effective fragmentation.

Pilot tests which replaced the water with spherical slugs of steel (3/16 to 2 in. diam.) resulted in spalling fragmentation and excellent specific energy values. Minimum values of specific energy appeared to occur with velocities below 500 fps. However, the evidence for the 2-inch spheres was limited by the fact that the 12-inch target cubes (sandstone, granite, basalt) shattered at velocities below 400 fps.

The tests suggest that moderate-velocity large slugs of water are not satisfactory for fragmentation of rock, but heavy large-sized solid impactors are very effective at moderate velocities.

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| | ROLE | WT | ROLE | WT | ROLE | WT |
| Impact, water | | | | | | |
| Impact, solid | | | | | | |
| Impingement damage | | | | | | |
| Fragmentation, rock | | | | | | |
| Erosion, rock | | | | | | |
| Rapid excavation | | | | | | |

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## ABSTRACT

Based on findings in other research areas it was reasoned that water slugs of substantial size (up to 1/2 lb) traveling at moderate velocities (< 800 fps) could impinge on rock with fragmenting pressure. To substantiate this reasoning, a compressed air launching gun was designed and built and an extensive series of impact tests was made on a steel-mounted pressure transducer and on sandstone and limestone targets.

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# A STUDY OF THE FRAGMENTATION OF ROCK BY IMPINGEMENT WITH WATER AND SOLID IMPACTORS

## I. INTRODUCTION

Current evidence [1,2,3]* demonstrates the existence of a high-priority need for improved technology relating to the rapid underground excavation of hard rock. This need pertains to a broad spectrum of our nation's social and economic problems. Its expression has been followed by a geophysics program in rock mechanics and rapid excavation funded by the Advanced Research Projects Agency and managed by the Bureau of Mines, Department of the Interior.

Of the many different functions involved in rapid excavation, the highest priority in new research has been assigned [1] to an improved method of rock fragmentation. This report deals with the research findings of a new program which was originally intended to provide a new and better method of rock fragmentation through the use of repetitive impact by large water slugs. In view of the initial findings of the program, the objectives were later redirected toward fragmentation through the use of repetitive impact by large solid slugs. The report reviews the rationale of the concept of rock fragmentation by impact and describes the facility used to test the concept and the test results on target rock.

## II. THE MECHANICS OF FRAGMENTATION BY IMPACT PRESSURES

The disintegration of cohesive materials by erosion with a water jet has a long history of application in the mining and transport of various alluvial formations and low-strength rock. High-strength rock has also been eroded by continuous water streams, but only in limited work areas and by inordinate working pressures (70,000 psi) in laboratory studies [4].

Serious consideration of the application of water jets in underground mining has in recent years led to trial operations in mining coal in the United States [5] and Britain [6]. These trials have used moderately high pressures (1200 to 3500 psi) with continuous water streams and have proven fairly satisfactory with coal having a compressive strength of about 2000 psi. There are no known examples of tunnel mining efforts in hard rock using

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*Numbers in brackets refer to references listed on pages 23-24.

continuous water jets, and there is no evidence that such jets can be used practically. However, more recent attention in the mining field has turned toward the enhanced disintegration that can be achieved with the pulsed impacting of interrupted water jets. The limited experimental studies by Voytsekhovskiy, et al. [7] in Russia, of Farmer and Attewell [8] and Brook and Summers [9] in England, and of Cooley and Clipp [10] in the United States do not clearly define the technique for use in tunneling, but some intriguing possibilities may be gleaned from their data.

Recent experimental developments in the United States which employ this approach have moved in the direction of very high (> 50,000 psi) jet generating pressures with jets of small size. While these developments have produced some very spectacular fragmentation results through the use of a combination of impact and stagnation pressures with a very high velocity jet, there is reason to believe that the high pressures inherent in the jet generating system would prove very difficult to handle in sustained field operations. In contrast, the current investigation exploits the "water hammer" pressure peak which occurs at the instant of impact of a water slug on rock. In this system the high fragmentation pressures occur only in the impactor and the rock, and the slug generator or launching system can work at quite moderate and manageable pressures. For example, in the single shot test gun described later, impact water hammer pressures in excess of 30,000 psi were achieved with a launching pressure of only 15 psi.

## A. Liquid Impact Pressures

If rock disintegration is to be accomplished with a liquid jet, one pressure which can be readily applied to the rock is the stagnation pressure of the jet stream. Since most liquid jets are produced basically by extruding the jet from an orifice in a pressure chamber, the stagnation pressure on a rock target will be nearly the same as the original chamber pressure, and the jet velocity $V$ will be approximated as shown in Fig. 1a and as given by the equation

$$V = \sqrt{2g\ P_1/\gamma} \tag{1}$$

where $P_1/\gamma$ = liquid pressure head in the chamber, $\gamma$ = specific weight of the liquid, and $g$ = gravitation constant. In some nozzle variations of the simple orifice [10] additional velocity is given to part of the fluid by a secondary acceleration mechanism.

If the front of the liquid jet is impinged or impacted on an essentially rigid body, there will for a fleeting moment be a compressive impact pressure, $P_2$, as shown in Fig. 1b. The value of $P_2$ is approximated by relating the change in kinetic energy to the work done in elastically compressing the liquid in a conventional "water hammer" type of analysis; thus

$$P_2 = K\rho c V \tag{2}$$

where $K$ = a constant which depends primarily on jet shape, $\rho$ = the liquid density, and $c$ = the velocity of an elastic wave in the liquid, which for water normally approximates or exceeds a value of 4700 ft/sec.

Following the impulsive impact of the jet front, the liquid will flow radially away from the pressure center and the pressure head will fall to the incompressible stagnation value as shown in Fig. 1c. This value, $P_3/\gamma$, is of course essentially the same as the initial chamber pressure head $P_1/\gamma$ and at moderate velocities is far less than $P_2/\gamma$.

If a pressure-measuring device could be fitted at the impact point and a record taken of pressure versus time, a simplified conceptualization of the results would look approximately like Fig. 2.

The duration, $T_1$, of the impulsive pressure $P_2$ is dependent on the diameter, $d$, of the impacting jet and can be roughly approximated by twice the time it takes the elastic pressure wave to travel from the jet center to its periphery, or a distance of $2d/2$. The duration $T_1$ will then be approximated by $T_1 \approx d/c$. The stagnation pressure $P_3$ will endure for a time $T_2 = L/V$ in which $L$ is the length of the jet. If the flow is steady, $L$ approaches infinity and the time $T_2$ is infinite; if $L$ is the length of a finite jet slug, $T_2$ will be finite.

To obtain some perspective on the magnitude of these pressure values as they might be employed in rock fragmentation, Eqs. (1) and (2) have been calculated for a substantial range of jet velocities. The resulting values of $P_2$ and $P_3$ for water are shown in Fig. 3. It should be noted that high water pressures can be achieved for either impact, $P_2$, or stagnation, $P_3$. However, stagnation requires markedly greater velocities than impact if the $K$ value of impact can be kept high.

More sophisticated forms of Eq. (2) have been evolved, but in view of our relative ignorance of values for the involved variables during high speed impact, the simpler equation serves for general comparisons.

The erosive effect of impacting small water drops has been known and studied for over 40 years, and the general validity of the water hammer theory of erosion is well documented [11,12]. However, these known processes relate to water masses which are well formed and coherent, a condition which occurs when the slug size is small enough to be dominated by interfacial surface tension forces. In addition, these studies dealt largely with steam turbine and aircraft raindrop erosion. In these situations the impacting water drop was essentially at rest and the solid target was in high speed motion. Such masses do have marked erosive character when impacted by high-speed targets, but their disintegrating influence is micro-scaled, and erosive removal occurs through creation of an end product with large surface areas and with consequent large energy demands per unit volume of eroded material. This energy criterion, known as the specific energy, might be greatly reduced if the material removed per impact possessed a substantial volume and relatively small surface area. This is inherently impossible with small drop systems, but is conceivable through the delivery of larger individual blows via larger individual water masses. It was the objective of this study to establish how large slugs of water could be delivered to a rock mass with an air-water interface sufficiently coherent to generate a strong elastic pressure wave approximating a water-hammer pressure value. It was recognized that the simple water-hammer expression must be adjusted to compensate for (a) the elastic response of the target rock to the impact, (b) basic changes in the values of $c$ and $\rho$ for both the water and the rock under high transient rates of loading, and (c) the geometric effects of the frontal configuration of the water slug. These adjustments, when introduced into the equation through the use of the coefficient $K$, may cause $K$ to vary from values slightly more than unity or may depress it far below unity. The resulting pressure values are typified by those in Fig. 3.

## B. Solid Impact Pressures

Pressure values resulting from the impact of a solid impactor on a solid target derive from the same basic equation [Eq. (2)] as was discussed for liquid impact. This is true because the same type of elastic absorption of kinetic energy is involved. Evaluation of the equation for a given velocity does, however, lead to markedly greater pressure values than for water impact. This is true because most solid materials suitable for impacting have a much greater density value (for steel 7.9 times that of water) and a substantially greater elastic wave velocity (for steel 3.6 times that of water). Some perspective on the magnitudes of these pressure differences can be obtained from the comparative graphic plotting of Fig. 3.

In addition to this basic increase in applied pressure values, the solid impactor also differs significantly in the duration, T, of the impulsive pressure. Since the impactor is not fluid, the peak frontal elastic pressure is not released laterally through the nearest free surface, but is sustained until the rear of the impactor is brought to rest. The duration $T_1$ is thus a function of the impactor's axial length rather than its lateral diameter, and added length should appreciably affect the target fragmentation.

## C. Response of the Target to Impact Pressures

A complete picture of the manner of failure of brittle rock under impact is not available at present, but related findings from mechanical drilling of rock, limited water erosion studies of rock, and extensive studies of water drop erosion of metals suggest that the following concepts, illustrated by reference to Fig. 4, form a reasonable approximation of the mechanics of failure with a water impactor:

1. Compressive indentation of the rock will occur near the pressure center of the impacting water mass and will be initiated by the impact pressure $P_2$; $P_2$ will be followed by the stagnation pressure $P_3$, and this in turn will fall to the ambient atmospheric pressure value when the jet ceases.

2. The impact pressure $P_2$ will elastically strain the rock (a) in major compression at the impactor center zone <u>A</u>, (b) in major tension in a circular zone <u>B</u> surrounding the compression center, and (c) in major shear along the surface of a shallow cone <u>C</u>.

3. If the pressure $P_2$ is small relative to the compressive and tensile strength of the rock, elastic recovery will occur when the pressure is removed and there will be no evidence of disintegration or erosion.

4. A number of secondary focal stresses will occur due to the action and interaction of a complex set of axial and lateral pressure waves within the rock body and a system of waves on the surface of the rock. For materials of low tensile strength this may result in tensile failure in Zone <u>A</u> during the pressure release following the initial compressive strain and may show ring cracks as at <u>D</u> due to the tensile phase of the surface waves.

5. As the relative pressure increases, small losses of material will generally occur first at <u>B</u>, followed by cracking at <u>D</u>.

6. Impacts at higher pressures may lead to appreciable material losses at <u>A</u> either from tensile failure with the release wave or, more significantly, when the pressure exceeds the crushing pressure of the rock.

7. Repeated impacts at high pressure or a single impact at a very high pressure may exert sufficient radial compressive force to complete shear failure along the conical surface, Zone <u>C</u>, with large losses of material. The terminal crater form <u>C</u> is attained in a number of stages of cratering represented by <u>C</u>' in Fig. 4.

8. In addition to the major stressing and disintegration due to the above-described application of pressure $P_2$ for time $T_1$, considerable secondary stressing, loosening, and flushing will result from the high radial velocity which occurs during the application of pressure $P_3$ for time $T_2$. There is evidence that in some cases this radial flow velocity may be several times the initial jet velocity V and may cause considerable small-scale erosion at surface irregularities.

9. The penetration S of the major compressive strain into the rock face can be roughly assumed to be the distance that a compressive wave will travel during the impulse period $T_1$. Since this time $T_1$ was previously shown to be $T_1 \approx d/c$, and since the velocity

of a compressive wave in most rock is about four times that in water, the penetration distance S of the high pressure values should be about 4d. It is apparent from this that large-scale conical spalling will occur most readily if a large penetration distance S can be achieved. This in turn requires an interrupted liquid jet of substantial diameter, but it does not require a long length. This mechanism probably accounts for the fact that present research using small but long jets has achieved good removal only when the value of pressure $P_3$ was raised to the failure values of the rock and supports the idea that large impactors employing the $P_2$ value should be studied. It is noteworthy that the impactor length need be only a few multiples of the diameter for full generation of the destructive pressure $P_2$.

10. The foregoing reasoning relates to rock failure when the impact is essentially perpendicular to the rock face. In drop erosion studies with durable materials, angular departures from the perpendicular served only to weaken the impact effect. However, the findings of Maurer and Rinehart with solid impactors [13] and of Fyall [14] involving angular impacting of a drop with a moving target indicate that an asymmetrical pattern of stressing does occur and that if stress values are sufficiently high, asymmetrical spalling may occur. Low angles are to be avoided, as they produce ineffective ricochet of the impactor. Asymmetrical initial breakout becomes more difficult as the strength of the rock increases.

11. Initial symmetrical breakout of rock from a solid plane face is more difficult than asymmetrical breakout of a surface near an edge or depression in the surface. Knowledge of the internal surfaces of shearing weakness near the edge of brittle rock is used to design the spacing or pitch of the bit-tooth in mechanical drilling devices [15], and Voytsekhovskiy, et al. [7], when disintegrating with a water jet, also found improved breakout with selected pitch distances between impact centers.

If liquid jets are to be employed to remove significant amounts of material in tunnel mining, it appears that crushing failures as per item 6 above, or better yet, conical spalling as per item 7, will be required. In any case the applied liquid pressure must exceed some critical crushing or elastic compression condition before the important shear or tensile failure can occur.

The response of rock to a solid impactor appears to be quite similar to the spalling type of fragmentation just described for liquid impacting. Intuitively it would appear that the solid impactor permits the exercise of frontal shape and that a wedge angle or sharpness of the front should appreciably affect the efficiency of spalling. However, drill bit studies [15] indicate that in percussion-type drilling, changes in the shape of the front are relatively insignificant compared to changes in the magnitude of the power delivered. The crater volume was found to be nearly proportional to the impact energy delivered. This implies that frontal shape or tool sharpness may be relatively unimportant in the impactor application considered herein. It should be recognized that the conventional percussion drilling bit is very similar in basic character to the solid impactors under discussion.

The foregoing discussions have assumed that both the solid impactor and the target remain intact during the elastic compression process. It is of course the objective of the impact to eventually fragment the target rock, but in the general case consideration should also be given to the use of a frangible impactor. Limited tests by others [16,17] using such impactors over a very large range of velocities indicate that fragmentation or fluidization of the target has a number of modes, and these depend on the relative nature of failure in the impactor and the target. Singh's data [16] suggest that at lower velocities relatively little damage occurs on the rock target if the impactor fragments. However, at hypervelocities the rock target fragments well despite prior fragmentation of the impactor.

The foregoing has been based on the need for substantial elastic compressive strain or crushing before tensile or shear fracture can become effective in major fragmentation. The compressive loadings required to produce failure in a given material are conventionally determined in a quasi-static compression testing machine using cubes or cylinders of limited dimensions. While compressive values for rocks determined on this basis are a relative indication of rock strength, they are by no means a clear indication of the pressure value at which the rock will fail under confining boundary conditions and under high rates of dynamic loading. It is, therefore, difficult to predict the unit impact loads that must be applied to produce fragmentation in rock. Hence the most realistic research tests will be those involving confinement conditions and loading rates consistent with the applications in mind. Limited data on systems providing loadings similar to the impact concept suggest, when applied to a large rock mass, that loadings of as much as ten times conventional compression values may be required to fragment many types of rock. Other data suggest much lower values.

It is also important to note that the ultimate failure mechanism is a shear or tensile rupture originating in some inherent weakness or fracture in the target structure. Measured values of failure must, then, somehow reflect the relative population of such weaknesses in the material which is being stressed. Since this population is probably inherent in the grain structure or formation of a particular material, the threshold values of failure loading should increase as the volume of critically stressed material decreases. Related evidence of this has shown up in many materials tests and is typified by the size-strength findings [18] of Fig. 5 and the size-energy findings [19] of Fig. 6. These suggest that whatever means are used to fragment rock, critical size effects may occur, and tests of the mechanism should include a substantial range of variation of the volume of rock which is stressed. It is for this reason that the impactor tests described herein were designed to include the maximum practical size of loaded area or impactor.

## III. THE TEST FACILITIES

The first portion of the study was given to the design and development of a single-shot gun or impactor launching device. It was the objective of the gun design to provide a facility in which full scale impactors and impactor velocities could be employed in the tests. This was believed to be essential to realistic tests inasmuch as there was reason to believe that the rock failure mechanism was inherently sensitive to size and speed. The resulting gun arrangement as shown in Fig. 7 is powered by a compressed air reservoir using plant compressed air at up to 26 psi to launch impactors of up to one pound in weight and up to 2 inches in diameter at velocities up to 1000 fps. The relatively low and safe air pressure was made possible by accelerating the sabot which carried the impactor in a 6-inch-diameter barrel of 20 ft length. The general design of the gun follows that of a somewhat similar unit described in Ref. [20]. The test impactor is retained in a frontal cavity in a foamed plastic cylinder which serves as the wadding or sabot of the projectile. For water impactors the basic length and diameter of the water slug were determined by the lined cavity provided in the sabot. For the solid spherical impactors the sabot was provided with a load-centering and load-distributing solid disk. The expendable sabot was arrested at the gun muzzle by an external structural framing and the impactor projected on through a limited hole in the arrestor. The arrestor arrangement is shown in Fig. 8.

The charged sabot was loaded into the gun barrel at the breech and the breech was fitted with an expendable thin plastic diaphragm which served as a pressure barrier between the air reservoir and the gun barrel. Sabot velocity was controlled by selecting the pressure to which the air reservoir was charged before firing. Firing was achieved by rupture of the diaphragm with an electrically controlled firing pin. The loading, firing, and velocity control of the developed system proved to be quite satisfactory.

The arrestor structure which stops the sabot and allows the impactor to project was fitted to permit the attachment of a variety of sleeves, orifices, and extrusion nozzles for exercising control over the diameter and frontal configuration of the air-water interface of the liquid impactor. For the solid impactor the orifice controls were removed to provide a large clearance hole. The configuration of the projected impactor was recorded by high-speed still photographs which could be taken at selected points in the variable firing range provided between the arrestor and the target or preceding the arrestor. Photo lighting employed a General Radio Co. strobotac model 1538-A which was triggered when the traveling impactor interrupted a suitably located light beam. The time interval between this light interruption and the interruption of a second light beam a short distance down range provided input for an electronic timer which permitted the slug velocity to be computed. The photographic and timing components proved quite satisfactory in general, but substantial difficulties were encountered early in the program because of false triggering due to the indefinite or incoherent front which occurred on the water slug. This problem will be discussed later.

In order to understand the response of a rock target to the water impactor it was considered necessary to first evaluate the pressure characteristics of the blow delivered by the water. To this end a target consisting of a flat steel plate was fitted with a flush pressure transducer to provide readout of the delivered transient elastic pressure pulse. A compromise involving physical size, sensitivity, maximum range, and ruggedness led to the selection of a quartz piezoelectric element housed behind a 0.25-inch-diameter stainless steel diaphragm. The calibrated unit, with a pressure range up to 70,000 psi, was transducer number 607C1 made by Kistler Instrument Corporation. The pressure transducer was connected with low noise cable to a Kistler Model No. 558 impedance converter, a Kistler Model No. 549GP coupler, and finally a Tektronix 561A oscilloscope for readout. The resulting voltage trace displayed on the scope face was photographed with an oscilloscope camera.

## IV. THE ROCK TARGETS

Rock target materials were selected from the BuMines-ARPA rock suite made available to ARPA contractors. Rocks used in the described test program consisted of Berea sandstone (Blocks 6 and 7), Salem (Indiana or Bedford) limestone (Block 7), St. Cloud Gray granodiorite (Block 5157-3), and Dresser basalt (Block 11). These materials were supplied in 1 ft cubes with essentially flat surfaces. Some of the average characteristics of the rocks as evaluated by BuMines [21] are shown in Table 1.

Table 1

ROCK CHARACTERISTICS

| | Berea Sandstone | Salem Limestone | St. Cloud Gray Granodiorite | Dresser Basalt |
|---|---|---|---|---|
| Comp. strength, psi | $6.45 \times 10^3$ | $5.53 \times 10^3$ | $32 \times 10^3$ | $51.3 \times 10^3$ |
| Youngs Modulus, psi | $2.079 \times 10^6$ | $2.666 \times 10^6$ | $10 \times 10^6$ | $10.4 \times 10^6$ |
| Shore hardness | 32.86 | 26.39 | 95 | 88 |
| Density, $g/cm^3$ | 2.1105 | 2.3381 | 2.7165 | 3.0117 |
| Pulse velocity, km/sec | 2.402 | 4.508 | 4.458 | 6.723 |
| Bar velocity, km/sec | 1.912 | 4.027 | 4.071 | 6.049 |
| Torsional velocity, km/sec | 1.396 | 2.555 | 2.920 | 3.798 |

## V. THE WATER IMPACTOR TESTS

### A. Generation of Water Slug

An extensive effort was made to generate a projected water slug of large diameter and good frontal definition. Various types of nozzles were installed at the arrestor plate in an attempt to create a coherent water slug. Some of these nozzles had straight sides with diameters of 7/8, 1-1/4, and 2 in., some tapered sides with angles of 2.5 and 10 degrees, and some sharp-edged orifices with diameters up to 3 inches. The cavity depth in the sabot was varied from one to 6 inches. High speed photographs were taken of the water slugs at velocities from about 250 fps to 900 fps at distances varying from 3 in. to 6 ft downstream of the arrestor plate. The photographs indicated that the water slug was surrounded by a fine spray of water droplets even at relatively small standoff distances. The front of the slug could not be maintained to the desired coherency. Some of the spray was eliminated through the addition of high-molecular-weight polymer additives to the water, but the results were still not satisfactory. Gelatine thickeners added to the water vastly improved the coherence of the slug, but extensive tests were not carried out due to practical considerations. No significant variation of the slug quality was noted with wide variation of arrestor geometry. Although continued extensive effort might have resulted in some improvement in the frontal definition of the water slug under controlled laboratory conditions, it was felt that in a prototype installation the slugs would probably be of the poor geometric quality observed in the tests. Thus it was of interest to proceed with evaluations of the pressure history of the impact and the damage to rock materials.

### B. Impact Pressure Tests

The previously described pressure transducer was installed in a thick steel plate and carefully aligned along the longitudinal axis of the gun barrel. A standoff distance of 12 in. was selected for the first tests. For each test shot the slug was timed and photographed, and the resulting impact pressure trace was obtained by photographing the oscilloscope face. A number of difficulties were encountered in the initial stages of the program. In the first firing, the oscilloscope was set to trigger on the first impulse received by the transducer. This resulted in false triggering by the spray in front of the slug and kept the desired record with the proper time base from being attained. Later tests were more successful after the triggering was changed to a pressure level corresponding roughly to the expected stagnation pressure. This permitted records of the impact pressure pulse at a suitable time scale and also of the drop of the pressure magnitude to the stagnation level to be obtained. A pressure diagram traced from an oscilloscope photograph is shown in Fig. 9. The pressure magnitudes indicated were based on the calibration of the pressure transducer as supplied by the manufacturer.

The coefficient $K$ to be applied to the impact pressure $\rho cV$ in this case is very close to unity. This particularly good record was selected as evidence that high impact pressures can be attained with a large diameter slug. However, it has not been possible to obtain slugs of the desired quality consistently. Additional data are shown in Fig. 10, in which the ratio of the peak impact pressure, $P_2$, to the stagnation pressure $P_3$ is plotted as a function of slug velocity. The ratio of the calculated simple water hammer pressure to the stagnation pressure is also shown for various coefficients $K$. The calculated pressure ratio decreases with increasing velocity. It can be seen that the data scatter widely over a range of $K$ values from 0.2 to 1.0. The time duration of the peak pressure pulse was also in general much lower than the previously rationalized $T \approx d/c$. It is felt that the attenuated pressure pulse is a direct consequence of poor frontal definition of the slug. Even small quantities of air entrained in the water front can greatly reduce the sound speed in the water. For example, at atmospheric pressure the sound speed is reduced from 4700 fps in pure water to about 300 fps with the addition of only about one per cent of air by volume. The deterioration of the value of $K$ in Fig. 10 with increasing velocities is believed to be due directly to an increasing deterioration of the slug as the kinetic energy content of the slug increased. These low values of $K$ at higher slug velocities can be carried into Fig. 3 for some comparative perspective. Such comparison suggests that damaging fragmentation of the ARPA rocks is not to be expected if many multiples of the rock test values are required to initiate damage on a large rock mass, as previously pointed out. Low $K$ values may arise also because the pressure transducer might not be located at the maximum pressure point of the delivered blow and because the transducer measures only an average pressure over its exposed area.

It was not possible to obtain pressure records at other standoff distances. During the last tests at the 12 in. standoff distance a component of the transducer system failed. Inspection and replacement of the component by the manufacturer were made too late in the program for additional evaluations at other standoff distances to be carried out.

C. Rock Fragmentation Tests

Following tests of the water impact pressure, a series of tests was initiated in which water slugs were impacted against a rock target. A variety of different nozzle shapes were utilized, and ten shots were made with each nozzle. The Berea sandstone target was positioned at 9 and 21 in. standoff distances. Although the damage to the rock was minor in all cases, best results were obtained with the 2 in. dia. straight nozzle. The rock was examined for damage after each shot. Visible damage was not observed until after about 3 shots. In general, the damage appeared to be erosive in nature with small pits forming a very shallow crater of about 2 in. diameter. Energy values were based on the total weight of the water carried in the sabot, 0.48 lbs, and the measured sabot velocity at the barrel exit. which was about 500 fps. The volume of rock removed was measured by filling the depression with size 100 glass beads and was based on an average of four measurements. At the 9 in. standoff distance, the specific energy for 10 shots impacting at the same point on the rock was 196,000 ft-lbs/cu in. (16,300 joules/cc). At the 21 in. standoff, the specific energy increased to 510,000 ft lbs/cu in. (43,000 joules/cc). Tests with higher slug velocities yielded no measurable damage. Limited tests with the Salem limestone target also showed no visible damage, and thus the test program utilizing water slugs as impactors was terminated. The number of launchings involved in both the pressure tests and the rock fragmentation tests totaled 550.

D. Conclusions

1. Generation of a large diameter water slug with a well defined frontal interface was quite rare even at modest velocities (500 fps). High speed photographs showed that the slug was surrounded by spray and water droplets, and the frontal face was not a smooth surface. Variation of the slug geometry

by using various types of nozzles did not provide the desired and necessary frontal quality.

2. Measurements of the pressure history of large diameter water slugs impacting a steel target fitted with a pressure transducer indicated that in general only a fraction of the water hammer pressure, $\rho cV$, could be obtained. Tests with slugs at various velocities have shown that the peak pressure varied from about 0.2 to one times the $\rho cV$ pressure, with most data points exhibiting the lower K values. High K values could not be obtained at higher velocities. In most cases the time duration of the peak pressure pulse was about 5 $\mu$ secs or less, indicating a poor frontal interface.

3. Tests with ten single impactions of water slugs with a velocity of about 500 fps on the same point on a Berea sandstone target showed little damage. These tests were carried out with various nozzle configurations and slug geometries. The damage that did occur consisted of minor small scale pitting with no evidence of spalling. The best specific energy values were 196,000 ft-lbs/cu in. (16,300 joules/cc) at a 9 in. standoff distance and 510,000 ft-lbs/cu in. (43,000 joules/cc) at a 21 in. standoff distance. Limited firings using Salem limestone as the target material resulted in no visible damage.

4. It is felt that the high specific energy values obtained in the water impact tests on the rock targets can be directly attributed to the lack of a discrete front on the water slug. This poor frontal definition resulted in relatively low impact pressures of very small time duration. Furthermore, the dynamic strength properties of the large mass rock targets at the high strain rates may have increased substantially over the static values, thereby reducing the probability of damage.

## VI. SOLID IMPACTOR TESTS

### A. Rock Fragmentation Tests

Steel ball bearings of 3/16, 1/2, 1, and 2 in. diameters were selected as impactors, although not all sizes were used with all target materials. Two tests were also made with high impact plastic spheres of 2.12 in. diameter. Rock targets were Berea sandstone, St. Cloud Gray granodiorite, and Dresser basalt. Each sphere was impacted against a new site on the rock with a trajectory of 90 degrees with the rock face except for the 2 in. spheres, which had a trajectory of 86 degrees. A standoff distance of 35 in. was maintained for all tests. The velocity of the projectile was measured with the timing device previously mentioned. Following each firing the crater characteristics were determined. Measurements were made of the crater depth or penetration, average diameter, and volume. Crater volume was measured by carefully filling the crater with a plastic modeling compound. The compound was removed and its volume measured. Some check tests of this procedure were also made in which the crater was filled with No. 100 glass beads. Good agreement was obtained between the two methods.

The first tests were made with the Berea sandstone as the target material. The impact of the steel sphere resulted in a crater consisting of a shallow cup of relatively large diameter and a cylindrical burrow of smaller diameter directly below the point of sphere contact. The burrow was found to be filled with crushed material which in this case was essentially sand grains. The loose material was removed from the burrow before the crater characteristics were evaluated.

It has been shown by Maurer and Rinehart [13] that the total penetration is a function of the momentum of the impacting sphere. Their data for two spheres of small diameter indicated no size effect. The present data, covering a wider range of sizes, are plotted in Fig. 11a, in which the momentum has been divided by the cross sectional area of the sphere. Although some scatter is noted, the relationship between momentum and penetration is essentially linear for all sphere sizes. Only one data point was available for the 2 in. diameter sphere. As a result of this test the sandstone block was completely fractured, even though the sphere velocity was only 84 fps. The depth of the shallow cup, not including the burrow (not the same as the total penetration of Fig. 11a), is plotted as a function of velocity in Fig. 11b. Here different curves are shown for each sphere size, although again it can be shown that the size effect can be removed by considering the momentum per unit area.

Penetration data for the harder rocks, granite and basalt, are plotted in Fig. 12. Data for the 3/16 and 1/2 in. diameter spheres impacting granite appear to exhibit no size effect, whereas the 1 and 2 in. diameter spheres show more penetration than would be expected on the basis of the smaller spheres. Data for basalt, shown by the crossed symbols, are similar to those for granite. The shape of the crater was different for the harder rocks than for the sandstone. A shallow crater of relatively large diameter was noted without a burrow in the center. Some powdery material was found in the center, although the extent was minor compared to that of the sandstone. The grain structure of the harder rocks was such that the crater bottom was not generally regular, and thus it was somewhat more difficult to measure the crater depth. This may account for some of the scatter of the data shown in Fig. 12, particularly for the larger sphere diameters.

Specific energy values were of primary interest in these limited tests. Kinetic energy was based on the sphere weight and the measured sphere velocity, and thus did not include any losses in the launching system. Figure 13 shows the data obtained for various sizes of spheres impacting a sandstone target at various velocities. For the smaller spheres the specific energy decreased as the velocity increased, with a minimum value of about 360 ft-lbs/cu in. (30 joules/cc) being attained at a velocity of about 400 fps. Essentially the same specific energy can be noted for the 2 in. sphere at a velocity of 84 fps. Additional data were not obtained with the larger sphere, as the sandstone block fractured completely after a single shot with an energy input of about 170 ft-lbs. This will be discussed further later. The minimum value of the specific energy is somewhat lower than that reported by Maurer and Rinehart [13] using 3/16 in. steel spheres and substantially lower than that found by Singh [16] using Zelux pellets. Furthermore, the minimum specific energy for Singh's data was attained at about 9000 fps, as compared to about 400 fps in the present data, disregarding the single data point with the 2 in. sphere.

Energy requirements using the solid impactors on the harder rocks, granite and basalt, are shown in Fig. 14 as a function of velocity. Data for basalt are identified by crossed symbols. The scatter of the data is greater for the harder rock than for the sandstone, although some trends can be noted. For the 1/2 and 1 in. diameter spheres, the specific energy may tend to decrease with increasing velocity, although data scatter makes this inconclusive. Data for the 2 in. sphere indicate somewhat more decisively that the specific energy increases with increasing velocity. It should be realized, however, that at sufficiently low velocities the specific energy may perhaps increase again if a threshold velocity is approached, and thus the specific energy should pass through a minimum. This threshold velocity has not been established in these tests for the larger sphere. A comparison of the present data with those obtained by Singh and Gault [16] reveals that the minimum value of specific energy of about 1200 ft-lbs/cu in. (100 joules/cc) occurs at a velocity nearly two orders of magnitude greater than that required by the current investigators.

The above specific energy values were based on the crater volume obtained with a single impact. In many cases, extensive cracks were observed extending outward from the crater. Successive impacts in the same general area would undoubtedly lead to larger volumes being removed. For example, in one firing of a 2 in. ball at a velocity of 226 fps, the point of impact was near a corner of the basalt block, 4 in. from each edge. The corner of the block was completely broken off from the cube after impact. Specific energy based only on the crater volume for this test was 1550 ft-lbs/cu in. (128 joules/cc). However, if the entire volume of rock removed from the original target was considered, the specific energy was reduced to about 30 ft-lbs/cu in. (2.5 joules/cc). Obviously, the latter low value of 2.5 joules/cc could not be obtained by directly impacting a massive rock face. It might, however, be approximated in edge breakout from an initial pilot hole first made in the face by multiple impacts involving values of the order of 100 joules/cc. The overall energy requirement of the dual operation might then be only a small fraction of the higher value of 100 joules/cc.

As in the case of the sandstone target, the granite and basalt cubes fractured completely under the impact of the 2 in. diameter sphere. Photographs of the three fractured blocks are shown in Fig. 15. The dark lines have been added to emphasize the fractures. For the sandstone block in

Fig. 15a, the energy of the impacting ball was 170 ft-lbs. The crater formed on impact can readily be seen. Failure of the granite block is shown in Fig. 15b. Here the first impact was at 350 ft-lbs, and the crater is identified by the number 570. No visible cracks were noted at that time. The next impact, number 573, of 685 ft-lbs fractured the block as shown by the dark lines. Apparently the block was weakened by the first impact. The other crater, number 574, was formed with an impact of 885 ft-lbs of energy. The small craters visible on the left side of the block were created by impacts of 1/2 in. diameter steel balls; no cracking was observed here.

The basalt block is shown in Fig. 15c. The lower left-hand corner was fractured as previously described. The failure of the block was a result of impact on the right face, where the crater can be seen. This failure was caused by two impactions in the same area, the first with a velocity of 377 fps (2640 ft-lbs) and the second with a velocity of 358 fps (2380 ft-lbs). No cracks were noted emanating from the crater after the first shot. The second shot resulted in the fracture shown in the photo.

The findings described above strongly indicate that additional benefits may be achieved by proper indexing of multiple shots at a given target. In many cases extensive internal damage to the rock structure had occurred following a single impact. The measured crater volume for a single shot did not reflect this additional damage. Succeeding impacts would thus result in larger volumes being removed, thereby reducing the specific energy to much lower values. Future tests to establish these trends on larger rock targets are strongly recommended.

The two tests with a 2.12 in. diameter high-impact plastic sphere impacting on the granite target at velocities of 300 and 600 fps indicated complete disintegration of the sphere with no visible damage to the rock material. The kinetic energies of 420 and 1760 ft-lbs, respectively, were comparable to those of a steel ball after which considerable damage was noted. This is in accord with the findings of Singh and Gault [16] as shown in Figs. 13 and 14 wherein frangible impactors failed to yield damage below a critical threshold velocity. In contrast, visual inspection of the steel impactors after a number of firings indicated only minor abrasion of the steel surface that had contacted the rock target.

## B. Conclusions

Although the preliminary data are too limited to completely establish trends, the following significant points are indicated:

1. Steel impactors provide a very high elastic impact pressure relative to water impact, thus permitting fragmentation pressures to be achieved with low impact velocities. Low velocities permit the consideration of low stress or low pressure with design potentials for long-lived launching mechanisms.

2. Steel impactors achieved fragmentation of hard rock with only minor effect on the impactor itself. Utilization of the magnetic property of steel in separating the impactor from tunnel muck would permit the consideration of a continuously recycling impactor launching system.

3. Expendable frangible solid impactors appear to require very large impact velocities to achieve the same rock damage which can be obtained using steel impactors at low velocity.

4. Crater depth for spherical steel impactors is a linear function of projectile momentum per unit area. Little or no sphere size effect was noted for sandstone, whereas for granite and basalt the larger spheres tended to give deeper craters than expected from the data with the smaller spheres.

5. Crater characteristics were similar to those in the previously described work of Maurer and Rinehart [13]. A shallow cup and a burrow existed for all sphere sizes in the sandstone, while only the shallow cup-shaped crater was observed for the stronger rocks.

6. For a sandstone target a minimum specific energy of about 360 ft-lbs/cu in. (30 joules/cc) was attained at a velocity of about 400 fps. Sphere size effect appears minor at the higher velocities, but is evident for the lower velocities. A single data point for a 2 in. diameter sphere indicates a comparable value of specific energy, but at a velocity of only 84 fps. Additional data for the larger sphere could not be obtained, as the block of sandstone fractured completely with the first 2 in. impactor.

7. Minimum specific energy values for sandstone were lower than those obtained by other investigators and occurred at velocities at least an order of magnitude lower.

8. Specific energy values for the stronger rocks (granite and basalt) indicate in general a marked effect of velocity and sphere size. Particularly attractive specific energy values were attained at velocities less than 200 fps for the 2 in. sphere. These values were similar to those obtained by Singh and Gault [16] at velocities two orders of magnitude greater than in the present tests.

9. In some cases, particularly with the 2 in. diameter steel sphere, it was noted that specific energy values based on single impacts may be conservative. Internal damage to the hard rock material occurred that was not apparent from casual observation of the rock surface. Repeated impact on the same rock face led to very extensive, large-scale cracking. In fact, the granite block fractured completely at an impact velocity of about 220 fps and the basalt block fractured at an impact velocity of about 380 fps. Impact near a free edge resulted in breakout of a large rock mass, indicating that very low specific energy values can be attained. It is thus anticipated that proper indexing of multiple shots adjacent to a pilot hole will greatly reduce the specific energy values.

10. From the foregoing data it appears conceivable that continuous non-cycling excavation processes could be developed with an average output specific energy value of 10 or fewer joules/cc. Since the mode of energy delivery could accommodate a substantial number of launching guns at a tunnel face, high continuous rates of energy delivery could be maintained to support a truly "rapid" excavation system.

11. Further studies are recommended for the optimization of size and velocity effects for individual impacts and preferred patterns or indexing of multiple impacts utilizing edge breakout.

12. The freely projected solid impactors used in these limited tests employed a standoff distance of 3 ft. Since a heavy impactor operating at low velocity generates little aerodynamic drag, very substantial standoff distances appear possible. Since a large standoff distance is desirable for flexible or mobile operations at a rough tunnel face, additional studies with larger standoff should be made.

## VII. ACKNOWLEDGMENTS

The authors wish to express their gratitude for the many contributions made to the study by their former colleague, John A. Almo, and by their colleague John M. Killen in the latter part of the program. Edward J. Mrosla and James V. Tarnowski were primarily responsible for the collection of the experimental data.

Credit is also due to Mr. Jacob N. Frank of the Bureau of Mines for the helpful cooperation he gave as Project Officer.

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# I L L U S T R A T I O N S

(Figures 1 through 15)

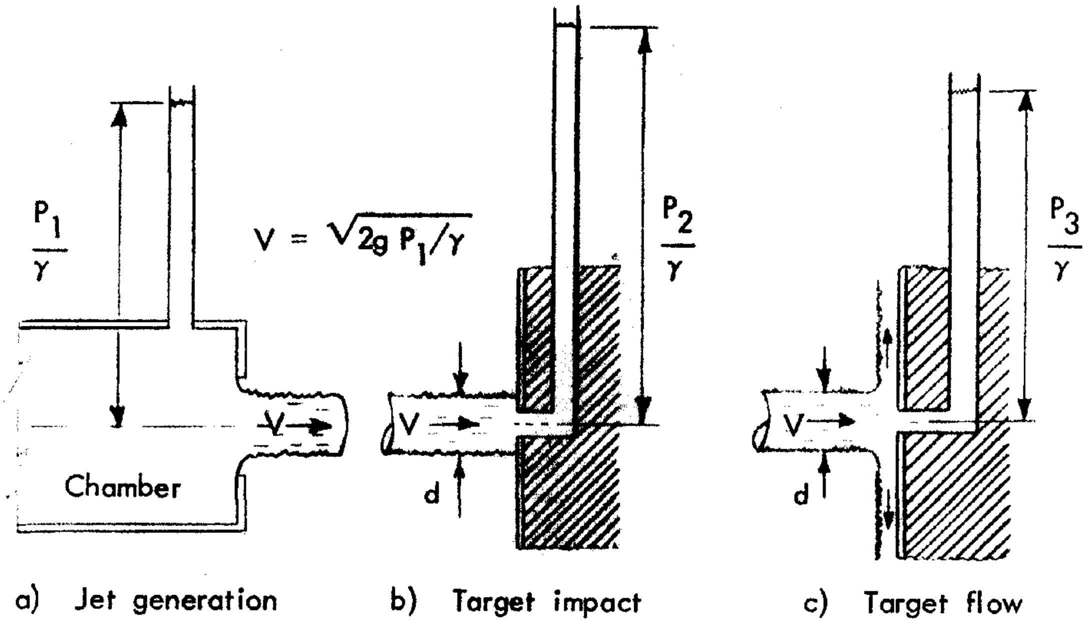



Fig. 1 - Water Jet Pressure Relations for Jet Generation, Target Impact, Target Flow

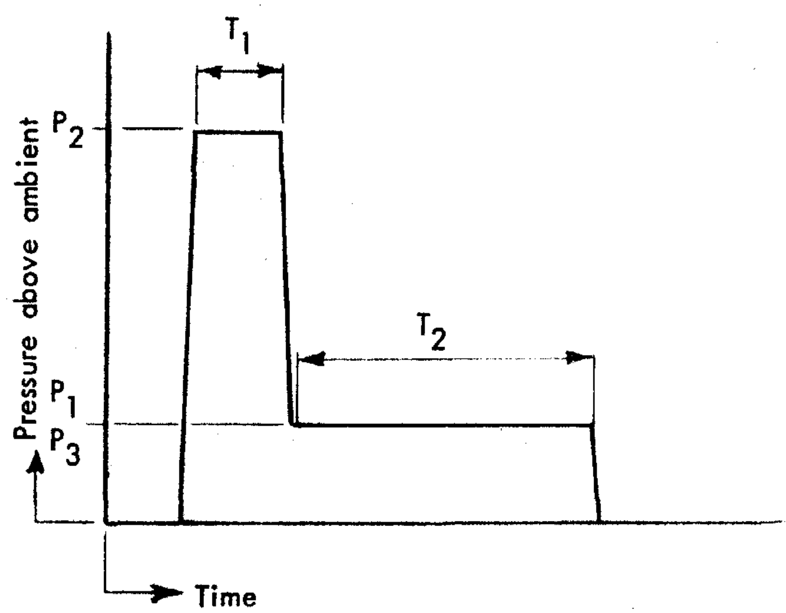



Fig. 2 - A Time History of Pressures Resulting from Water Impact

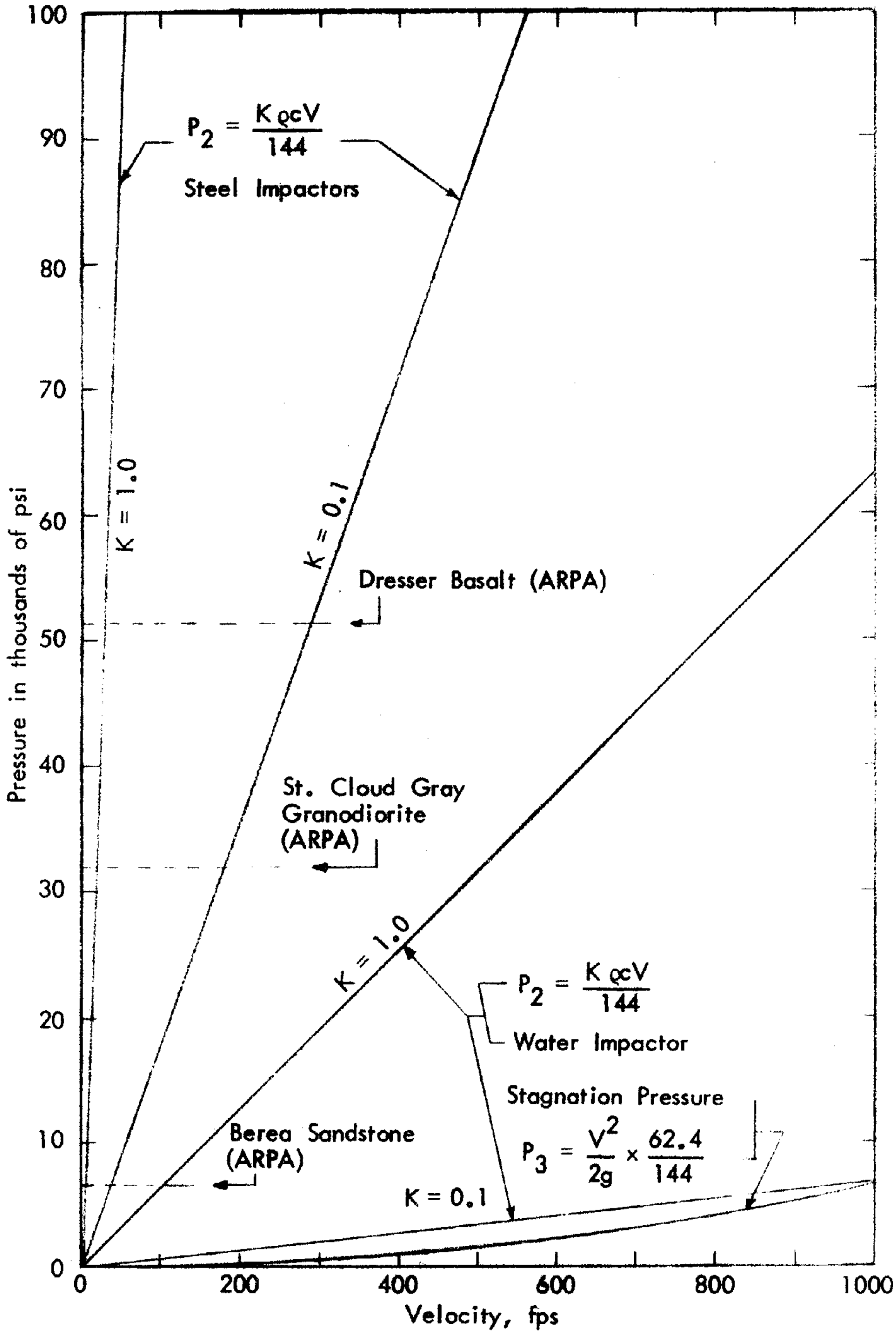



Fig. 3 - A Comparison of Rock Failure Values with Elastic Impact Pressures Generated by Water and Steel Impactors and by Water Jet Stagnation

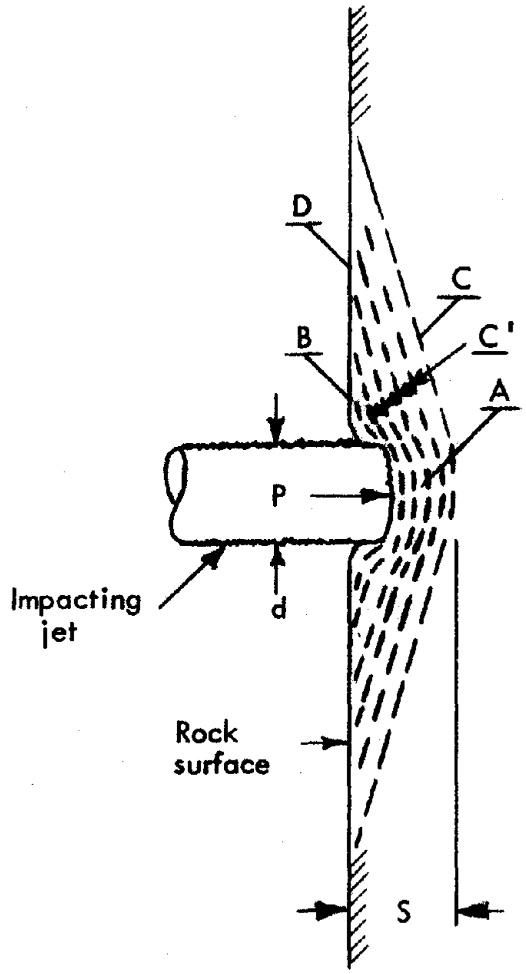



Fig. 4 - Zones of Rock Failure by Impact Pressure

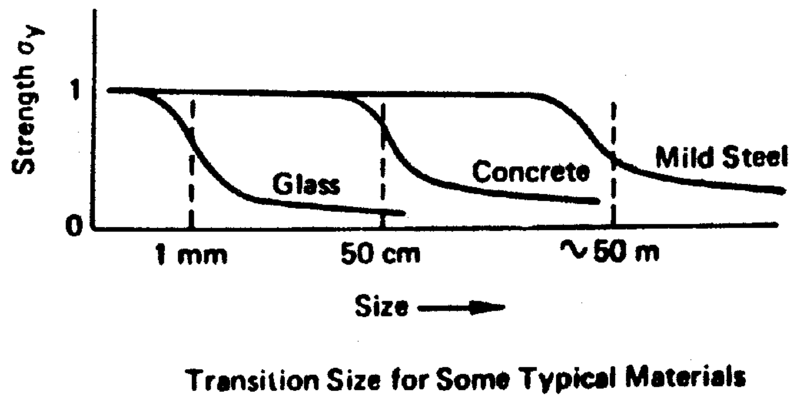



Fig. 5 - Size-Strength Characteristics of Materials
(from Glucklich [18])

*Typical Specific Energy Requirements for Conventional Crushing (joules/cm³).*[a]

| Rock | Crushed particle size | | |
|---|---|---|---|
| | 0.1 mm | 1 mm | 10 mm |
| Glass | 30 | 10 | 3 |
| Sandstone | 110 | 35 | 11 |
| Limestone | 110 | 35 | 11 |
| Dolomite | 110 | 35 | 11 |
| Quartzite | 120 | 38 | 12 |
| Quartz | 120 | 38 | 12 |
| Granite | 140 | 45 | 14 |
| Shale | 150 | 48 | 15 |
| Taconite | 180 | 57 | 18 |
| Basalt | 210 | 67 | 21 |

[a] Ref.: Bond.

Fig. 6 - Size-Energy Characteristics for Crushing Rock
(from Maurer [19])

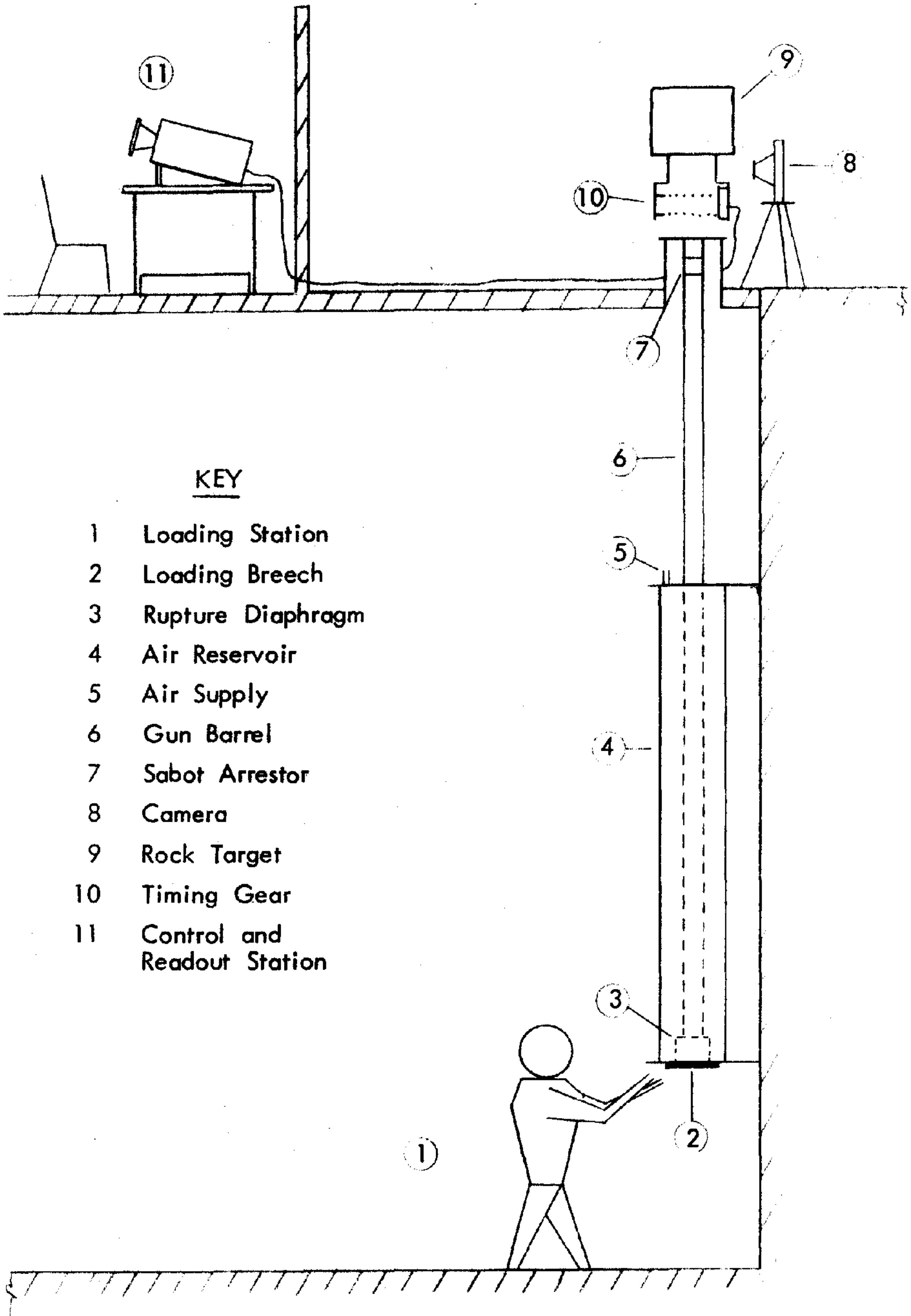
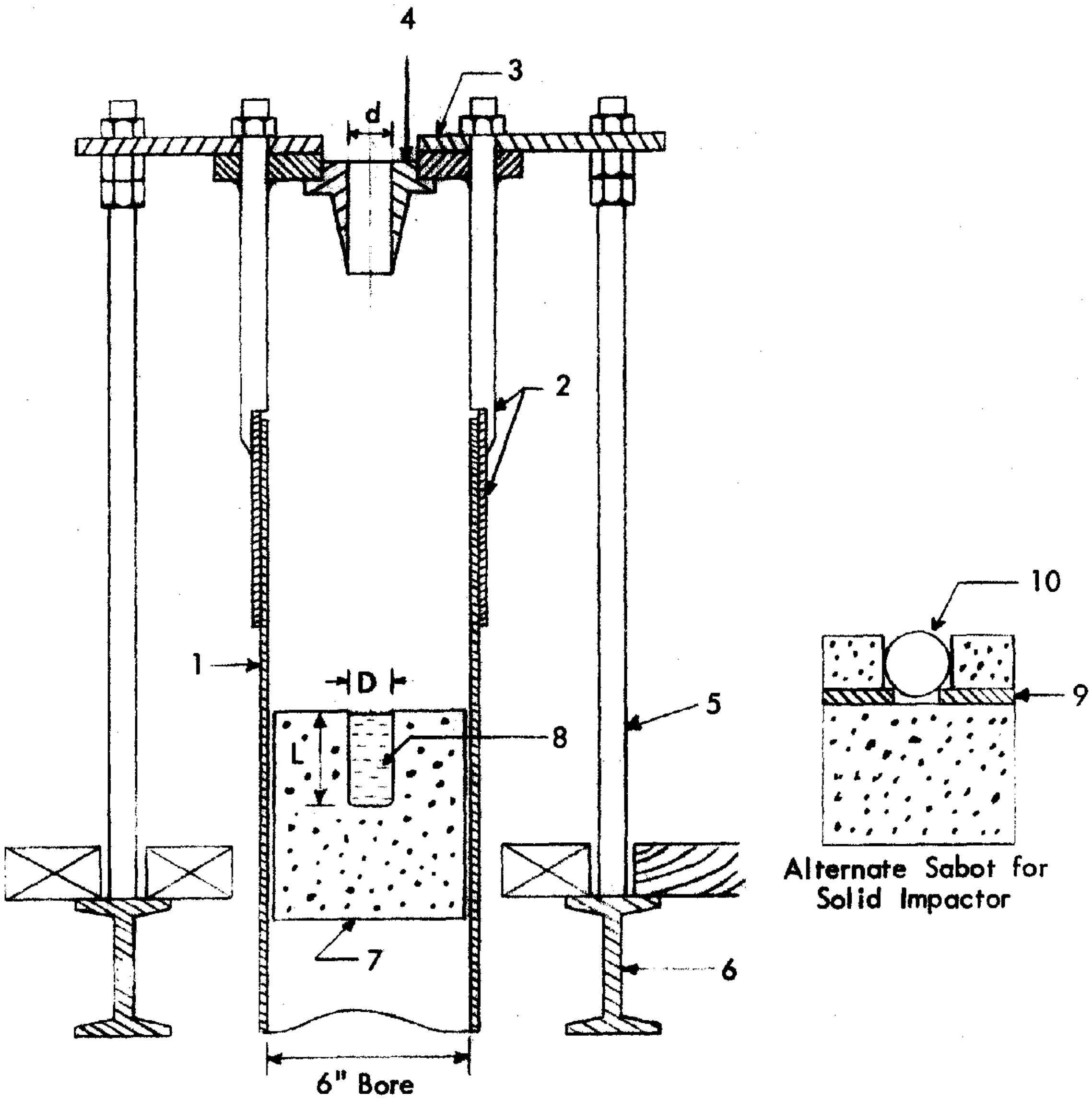



Fig. 7 - Arrangement of the Impactor Launching Gun




KEY

1 Gun Barrel
2 Alignment Sleeve and Vent Cage Unit
3 Arrestor Plate
4 Arrestor Nozzle (straight, contracting, or omitted)
5 Arrestor Rod
6 Arrestor Framing
7 Rigid Foamed Plastic Sabot
8 Water Charge
9 Plywood Ring
10 Solid Impactor

Fig. 8 - Sabot and Arrestor Arrangement

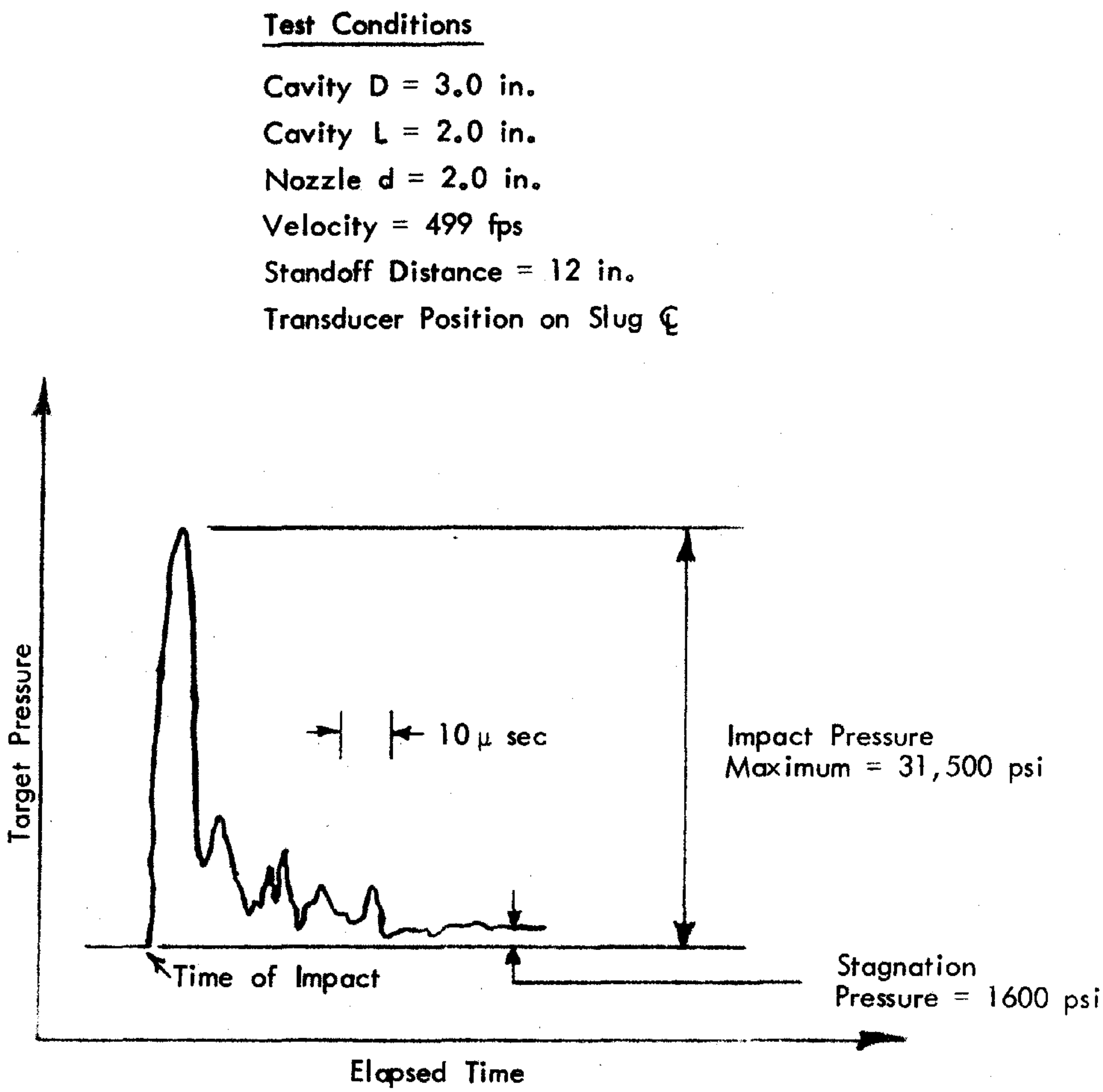



Fig. 9 - Measured Pressure History of Impacting Water Slug

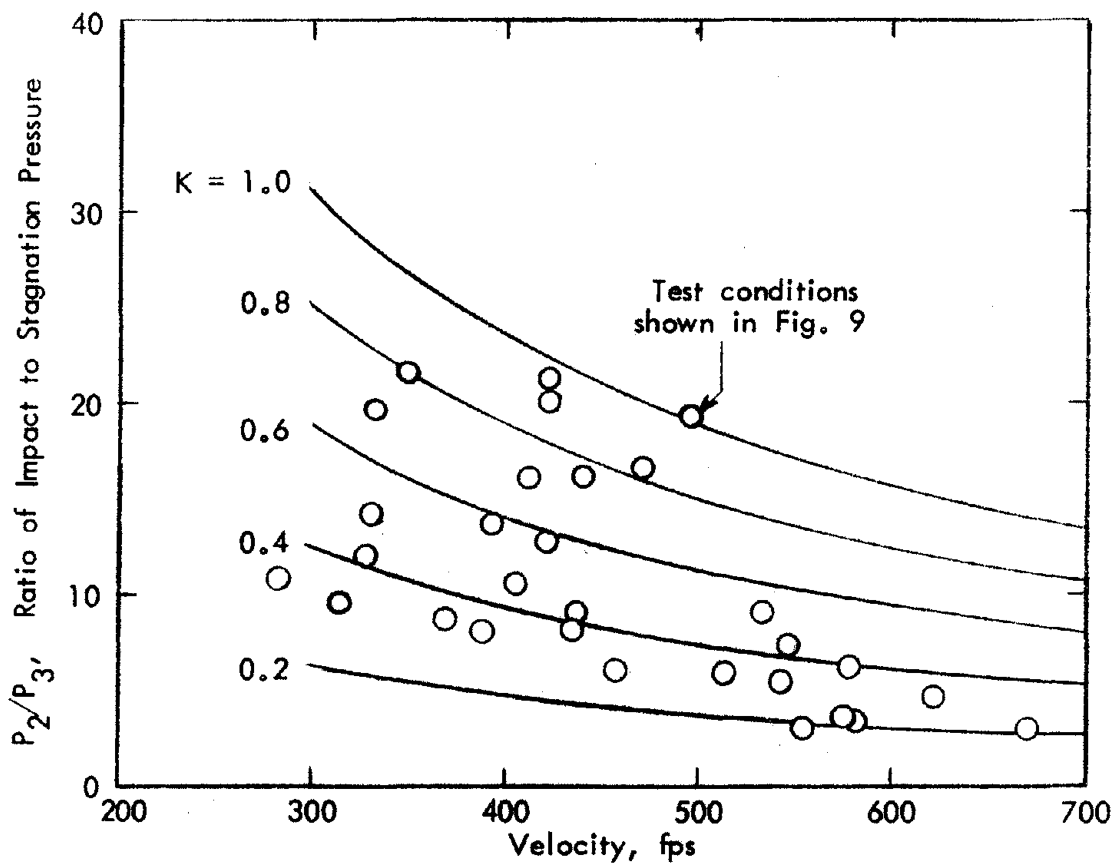



Fig. 10 - Peak Impact Test Pressures as a function of Velocity

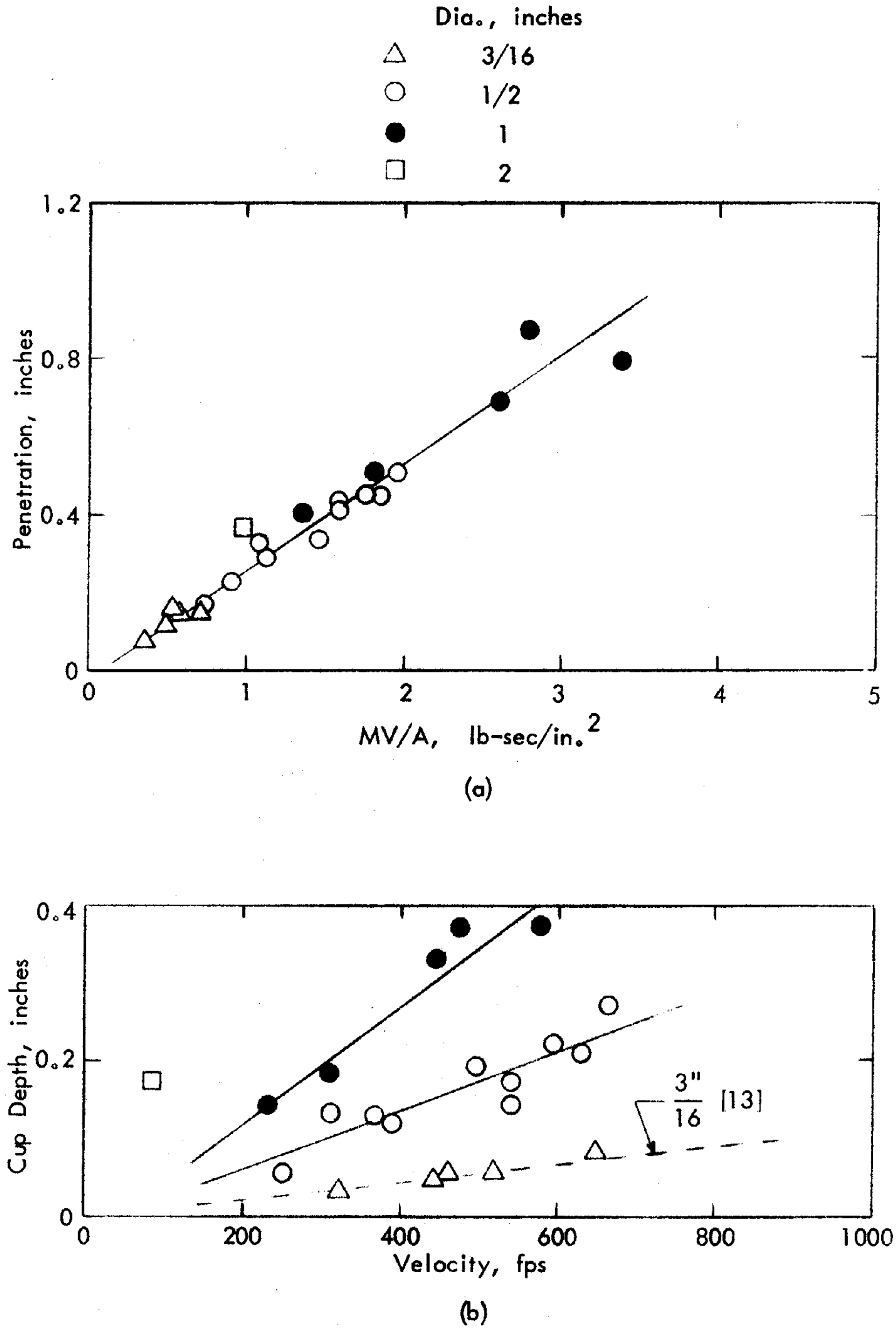



Fig. 11 - Penetration and Cup Depth for Berea Sandstone - Steel Spheres

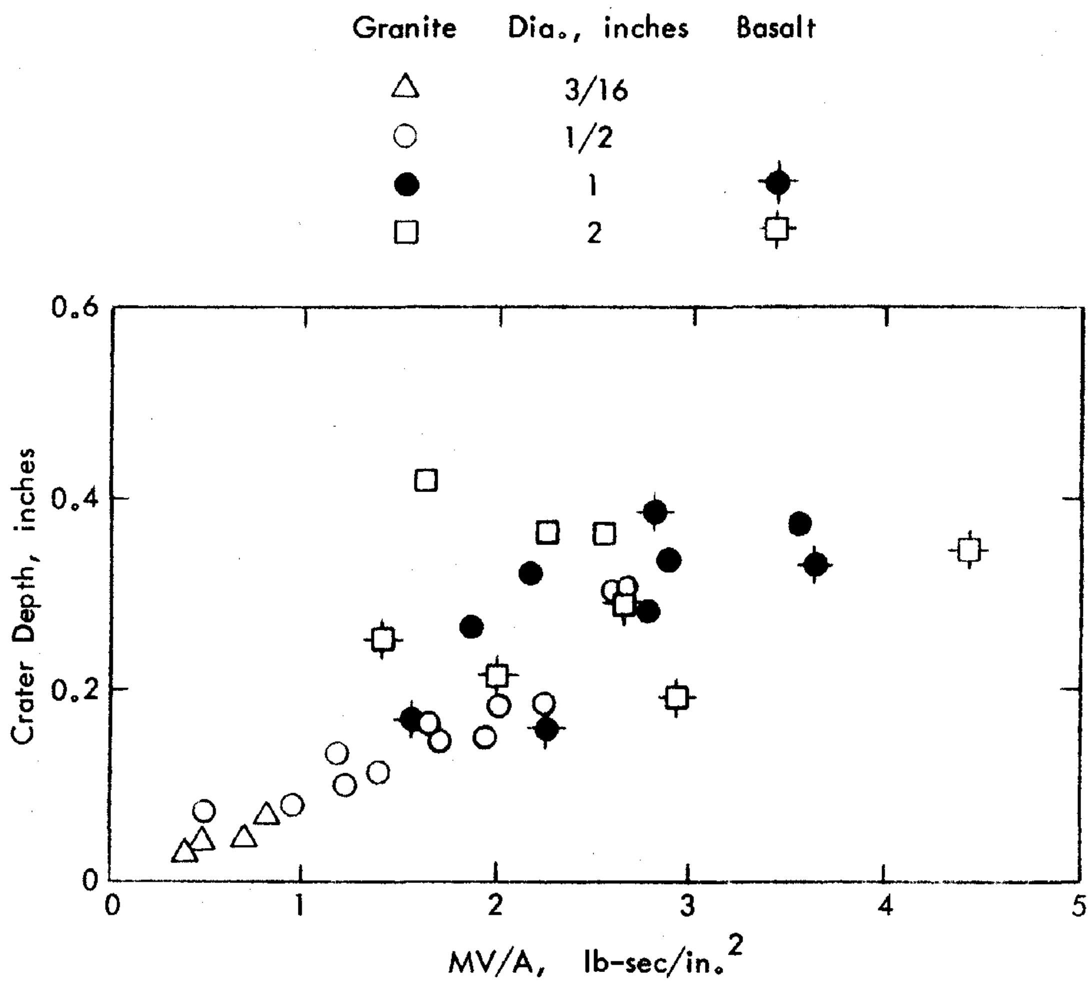



Fig. 12 - Crater Depth for Granite and Basalt - Steel Spheres

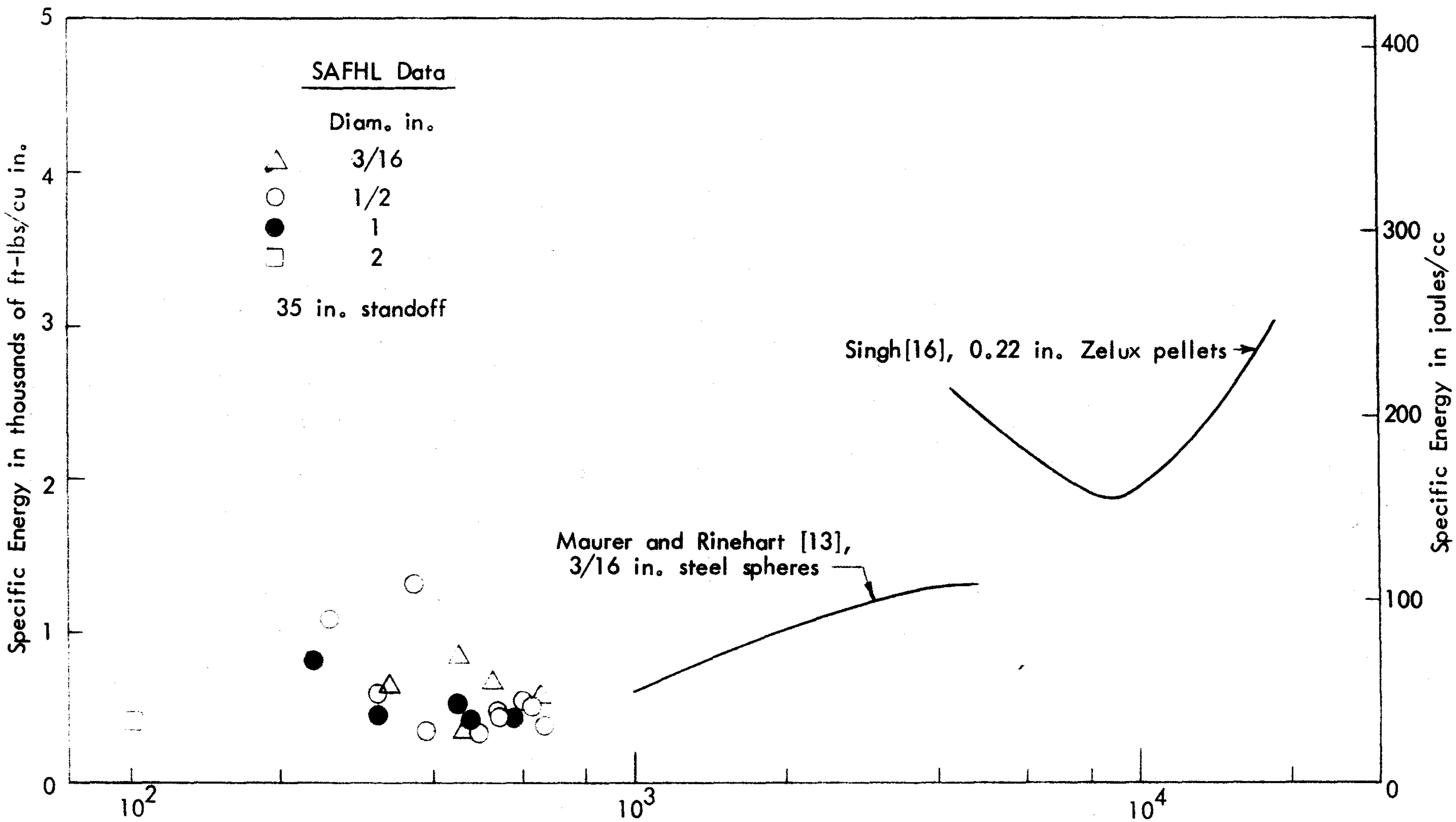



Fig. 13 - Energy Requirements using Solid Impactors on Sandstone

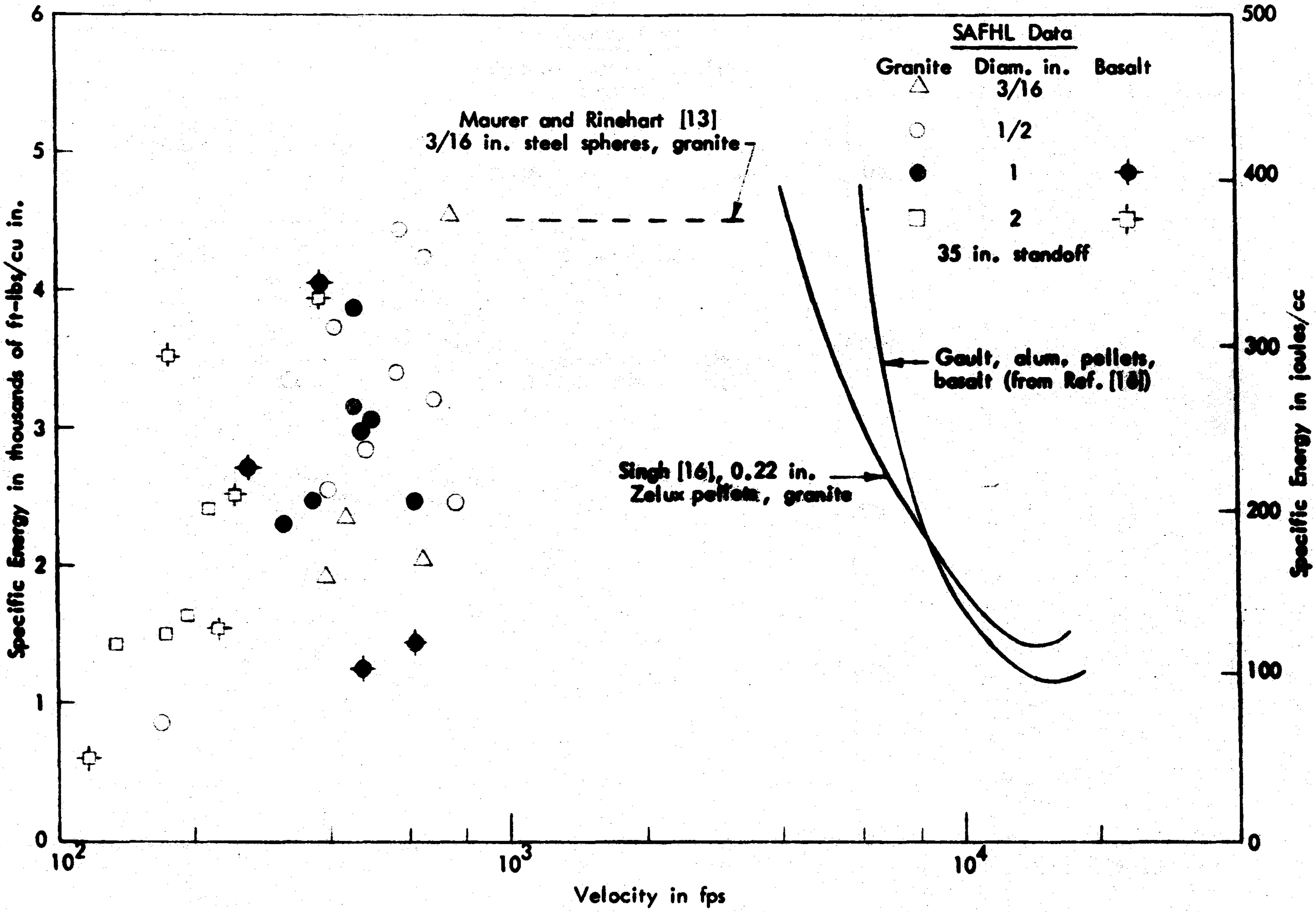
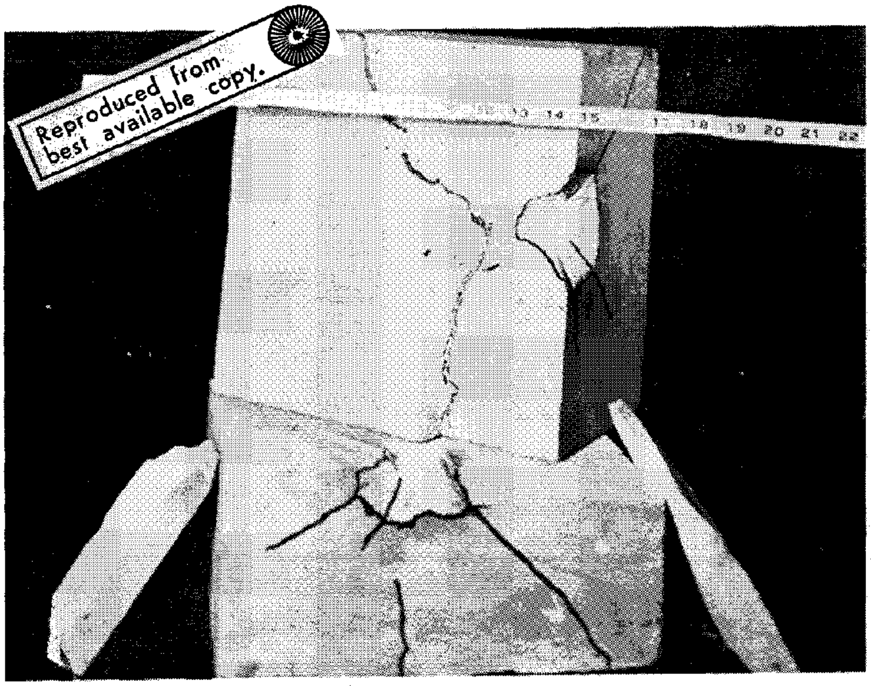
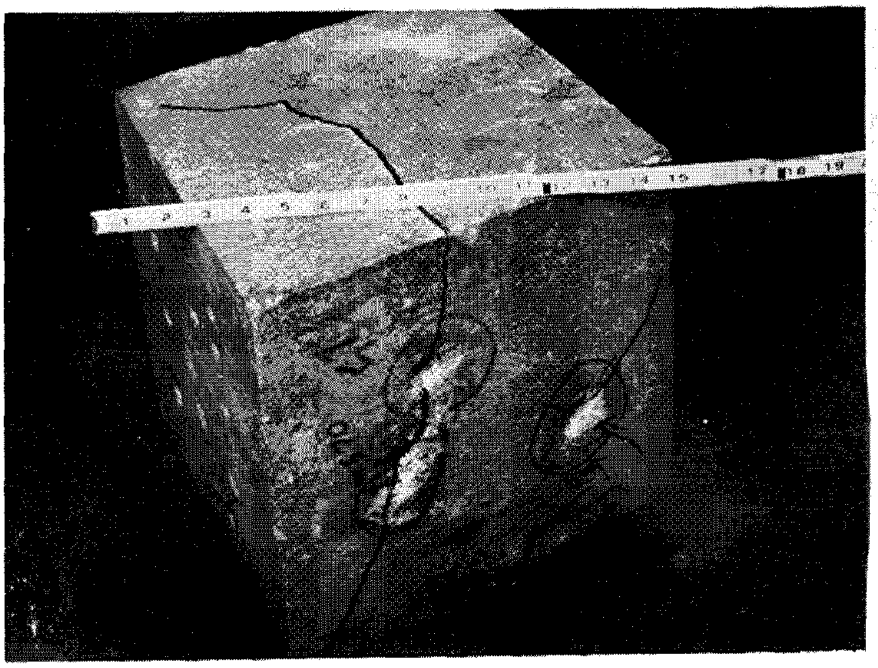



Fig. 14 - Energy Requirements using Solid Impactors on Strong Rock

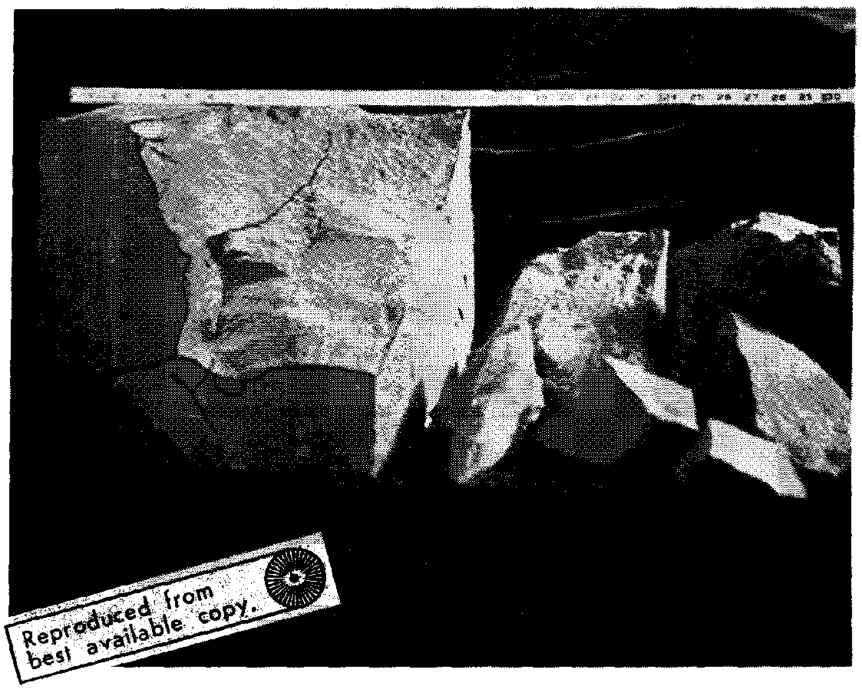



a) Berea Sandstone



b) St. Cloud Gray Granodiorite

Fig. 15 - Rock Targets Fractured with Impact of 2 in. Diameter Steel Sphere




c) Dresser Basalt

Fig. 15 - Rock Targets Fractured with Impact of 2 in. Diameter Steel Sphere [Continued]